Effects of Beam Plugs and the Hadron Hose

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Abstract

Placing an absorber ("beam plug") in the NuMI beam after the target can reduce the high energy tail of the neutrino spectrum for the low energy beam. This has important ramifications for any search for $\nu_\mu \rightarrow \nu_e$ oscillations. When a high energy ν_μ interacts via neutral current it can produce a signature which may be difficult to distinguish from those produced by low energy charged current ν_e interactions. This note presents Monte Carlo studies of neutrino interaction spectra with various beam plugs both in the presence and absence of the Hadron Hose. These studies started out as part of a study of the $\nu_\mu \rightarrow \nu_e$ sensitivity in MINOS [1] and adds to the studies done in NuMI note B-543.

Contents

1 Introduction

Previous studies [2] by IHEP have shown the effect on the ν_μ low energy beam spectrum of a hadron absorber (beam plug) placed in the beam after the first horn. The plug was optimized in diameter and length to reduce the tail of the high energy ν_μ spectrum. The optimum was found to be a graphite cylinder of 31.7 mm in diameter, 1.5 m in length and starting at z = 4 m. Using such a plug the high energy shoulder and tail ($E_\nu > 6$ GeV) would be reduced by about 60%. Studies of heating and stressing by the proton beam that were done in [2] are not repeated here, rather attention is focused on the effects of different plug designs and the hadron hose (an element not used in IHEP's work) on the low energy spectrum.

The reason to worry about the neutrinos in the high energy tail is that they can interact via neutral current (NC) and produce events which are difficult to distinguish from low energy electron neutrino charged current (CC) interactions, such as would be expected in $\nu_\mu \to \nu_e$ searches. The majority of background to these searches come from ν_μ NC interaction and half of this comes from energies above 10 GeV. [1]

The primary criterion in designing a beam plug is to minimize the high energy tail in the ν_μ spectrum while not decreasing the peak of this spectrum as this will cause a loss of statistics in both the disappearance and appearance searches. Of course, any material placed in the beam can absorb hadrons before they get a chance to produce useful neutrinos. The philosophy used in this study is that a reduction in the useful hadrons can be suffered as long as this reduction is small compared to other inevitable losses (beam line or detector down times being one such source of lost statistics). No hard criterion value was used as it will be shown that reductions in the peak are only of a few percent.

Another design criterion is that any beam plug design should not have a large impact on systematic uncertainties. Systematic effects due to the use of a beam plug as well as its alignment and dependence on the hadron production model used are shown.

In addition to various beam plugs, these studies use Monte Carlo[1] simulations both with and without the Hadron Hose [3, 4, 5]. The plug and hose play complimentary roles. The hose increases overall flux, by about 20% to 25% for muon neutrinos below 6 GeV and about 50% to 70% above. While an increase in statistics in the low energy peak is beneficial to both the appearance and disappearance searches, the increase in the high energy tail leads directly to an increase in the background for the $\nu_\mu \to \nu_e$ search. On the other hand, incorporating a plug counteracts this by strongly reducing the tail but at the same time slightly reducing the low energy peak.

This report has two main parts. The first shows the effects of various mixes of beam plugs and the hadron hose on the expected interaction spectra at the near and far detectors. The second presents various systematic effects.

[1] The program GNUMI was used for all simulations presented here.

2 Interaction Spectra

2.1 Types of Beam Plugs

Various types of beam plugs were considered. The "base line" beam plug for this study was taken to be the optimized one[2] found in the IHEP study[2]. This plug is a graphite cylinder of 3.0 cm diameter, 1.5 m long and starting at z = 4 m. Figure 1 shows a diagram of the placement of this plug in the target area. From this starting point different lengths, materials and placements were considered. Table 1 gives a summary of the different plug parameters. In this note, if no descriptive qualifier is used then it is the "short" beam which is being discussed.

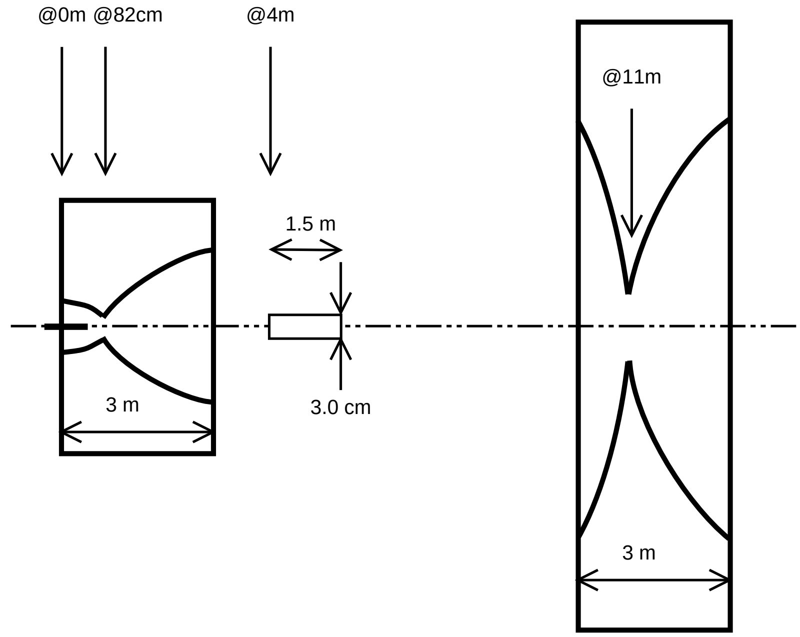

Figure 1: Beam plug location. Note that X and Y scales are vastly different.

2.2 Effects of Short Graphite Plug and the Hadron Hose

As stated above, the general effect of a plug is to reduce the high energy tail of the ν_μ spectrum by a lot and the low energy peak by a little, while the hadron hose increases both, with a relatively higher increase in the tail. Figure 2 shows the changes in this spectrum with and without these beam line elements.

[2] The final radius chosen in the IHEP study was based on available graphite stock. For this study the idealized optimum was taken.

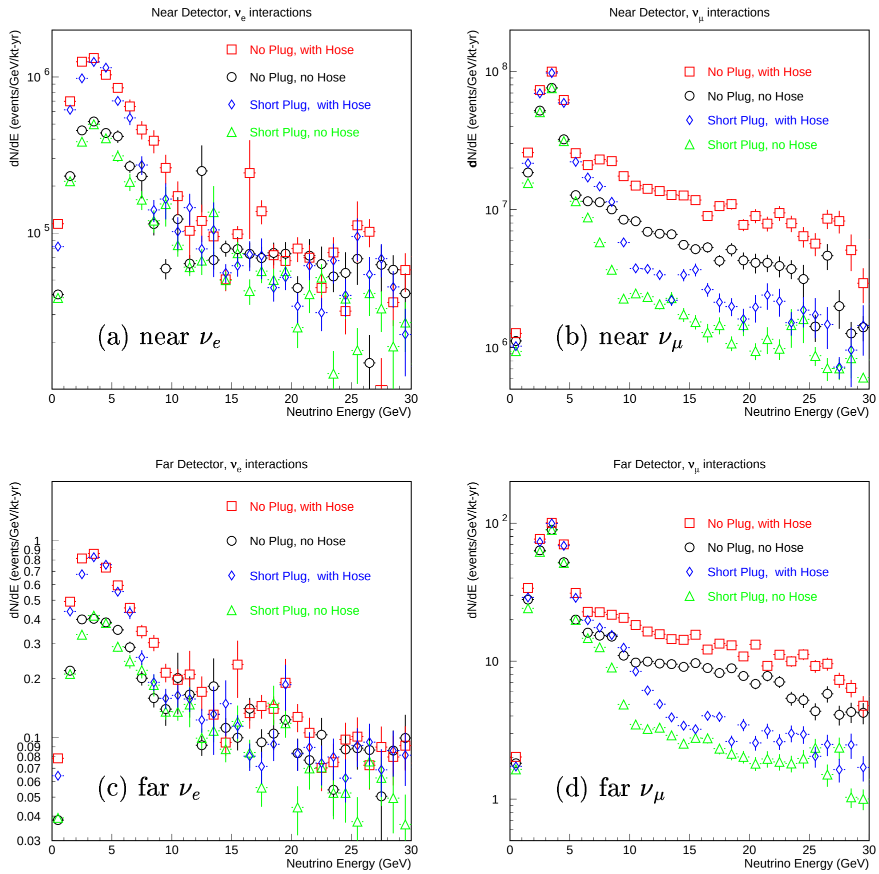

Figure 2: Neutrino, near and far detector interaction spectra with combinations of hadron hose and the short graphite plug. Data shows: No plug with hose (□), no plug no hose (○), with plug with hose (◇), and with plug no hose (△).

Name	Material	Length	Location
"Base line"	No plug		
"Short"	Graphite	1.5 m	4.0 m
"Long"	Graphite	2.5 m	3.5 m
"Copper"	Copper	1.5 m	4.0 m
"Composite"	Graphite/Copper	1.5 m / 0.3 m	4.0 m

Table 1: Summary of the parameters of the various beam plugs studied. All plugs are coaxial with the beam. Location refers to the distance from the front face of the first horn to the front face of the beam plug. The composite plug has a 0.3 m copper cap at the downstream end. All plugs have a diameter of 3 cm.

It is illustrative to break up the spectrum into various regions. The oscillations are expected to have a minimum around 1 to 3 GeV, which covers about half of the "peak" which extends to about 6 GeV. There is then a "shoulder" to 10 GeV. Above 10 GeV is taken to be the "tail". Table 2 shows the percent change in these regions between various beam line configurations. Some of the beam plug configurations will be discussed in more detail later.

Beam line config.		Energy range (GeV):			
From:	To:	0 - 3	3 - 6	6 - 10	10 - 50
BL	BL+HH	+20%	+25%	+53%	+68%
BL+HH	BL+HH+SBP	-7.6%	-2.5%	-26%	-70%
BL+HH	BL+HH+LBP	-10%	-3.4%	-41%	-82%
BL+HH	BL+HH+CuBP	-11%	-4.8%	-38%	-85%
BL+HH	BL+HH+CBP	-8.6%	-3.1%	-30%	-79%

Table 2: Percent changes in number of ν_μ interactions in the far detector when going from one beam line configuration to another. BL = Base line beam configuration (no plug, no hose), HH = with hadron hose, SBP = "short" graphite beam plug, LBP = "long" graphite beam plug, CuBP = "copper" beam plug, CBP = "composite" graphite+copper beam plug.

The hose increases the expected number of far detector events in the low enegy peak by about 20% to 25% while increasing this in the shoulder and tail by 50% to 70%. Adding in the short graphite plug will knock down the gain in the peak by a few percent. Unfortunately this reduction is largest at the low end of the peak where effects of neutrino oscillation are expected to be most prominent. Here 7.6% of the 20% increase the hose gives is taken away by the plug. With hose and plug in place there is still a net gain in the region of the peak compared to the case of neither hose nor plug.

2.3 Other Plug Designs

Adding more material to the plug will help reduce the high energy tail even further, but increasing the plug dimensions tends to cause the useful hadrons to be absorbed as well. The past studies [2] found that increasing the radius lead to a stronger reduction in the low energy part of the low energy peak as did, to a lesser extent, increasing the plug length. Increasing the length and changing the composition is examined in this section.

2.3.1 Long Graphite Plug

Adding on 0.5 m to each end of the "short" graphite plug gives the "long" graphite plug. The radius is the same. See Table 2 for percent changes in various energy ranges. Figure 3 shows the far detector ν_μ interaction spectra for the case of the hadron hose and no plug, short and long plug relative to the no plug, no hose case.

The same tradeoff observed in the previous IHEP studies is seen here. There is a desirable further reduction of 10% to 20% in the tail but it is accompanied by an additional couple of percent suppression of the low energy peak.

2.3.2 Copper Plug

A copper plug was considered as a way of placing more material in the beam without presenting a larger profile. However, it was learned [6] that copper is a poor choice as it would be destroyed by beam heating by a direct hit by the full beam. This being a possibility that must be planned for, the idea of a solid copper plug was excluded. In any case, the 1.5 meter copper plug performs about as well as the "long" graphite plug, so this optimization is not of value.

2.3.3 Composite Copper/Graphite Plug

It was found that the short graphite plug reduces the high energy tail so well, that a significant part of what is left in the tail is actually from hadrons produced in the plug by the protons in the primary beam which survive the passage through the target. Since the plug is acting as a bare target, the "useful" hadrons tend to be very forward going and thus exit the plug from the end cap. These two results are shown in Fig. 4.

This lead to the idea [7] of "plugging the plug" by adding a denser end cap. This was expected to reduce the high energy tail further while not being vulnerable to a full proton beam hit. A simulation with an additional 30 cm of copper just following the short graphite plug was run. The results are shown in Fig. 5. It shows the far detector ν_μ interaction spectra with this composite plug in place relative to that of just the short graphite beam plug. Also shown is the case of no plug. All plots have the hose turned on. It can be seen that adding the copper end cap results in an even further reduction beyond that due to just the short graphite plug. This further reduction is about 30% in the tail while only about 1% in the peak.

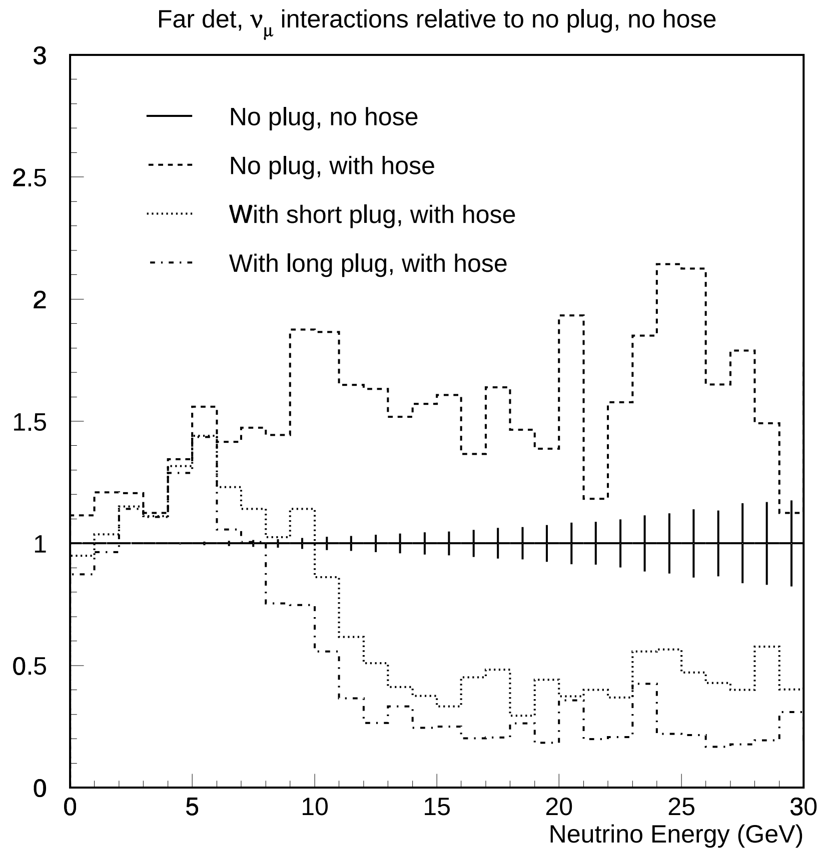

Figure 3: Far detector ν_μ interactions relative to no plug, no hose (solid line) case for the cases of the hose and no plug (dashed), short plug (dotted) and long plug (dot-dashed). The error bars show normalized statistical errors.

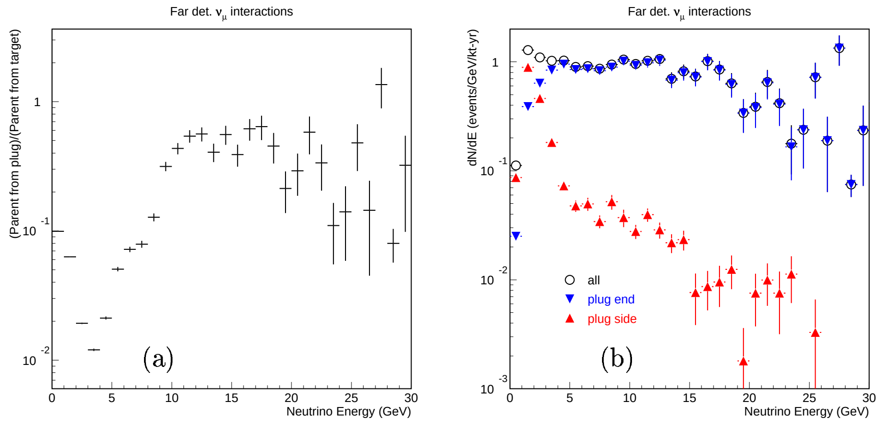

Figure 4: Far detector ν_μ interactions due to (a) parents produced in the short graphite plug relative to those produced in the target and (b) broken up by parents which exit the side of the plug ($\triangle$) or exit the end of the plug ($\bigtriangledown$) and their sum ($\circ$).

2.4 Other Plug Locations

In addition to the different plug designs presented in the previous section, different locations for the "short" graphite plug were considered. Figure 6 shows the far detector ν_μ interaction spectra for the case of the short beam plug moved to two different locations relative to the nominal location (z = 4 m).

Moving the plug closer to the first horn helps to reduce the shoulder of the spectrum but also reduces the high energy side of the low energy peak. This could be advantageous for $\nu_\mu \to \nu_e$ searches and not detrimental to disappearance searches depending on where the value of the oscillation parameters lay. If the minium oscillation probability is at low energies ($E < 3$ GeV), the appearance search would benefit from a reduction of neutral current background from the lower energy neutrinos in this shoulder, but if the oscillation probability has a minimum at energies around 7 - 8 GeV, then both searches will suffer a reduction in statistics of more than a factor of 2 from the case of the plug being at the nominal location.

3 Systematic Effects

Like the addition of any major element, adding a beam plug will cause a large perturbation on the the resulting neutrino beam. Some of this perturbation is by design and some is accidental or even undesirable. This section presents some studies of these systematics associated with adding a beam plug.

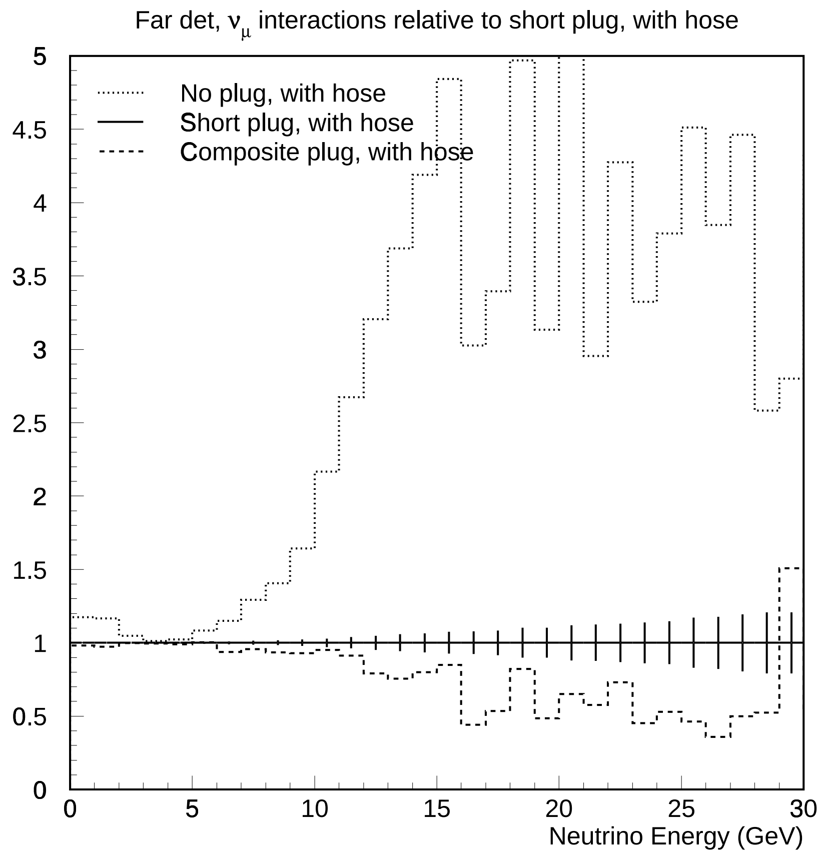

Figure 5: Far detector ν_μ interaction spectra with (dashed) composite plug and hose in place, relative to (solid) short graphite plug. Also shown (dotted) case of no plug, but with hose.

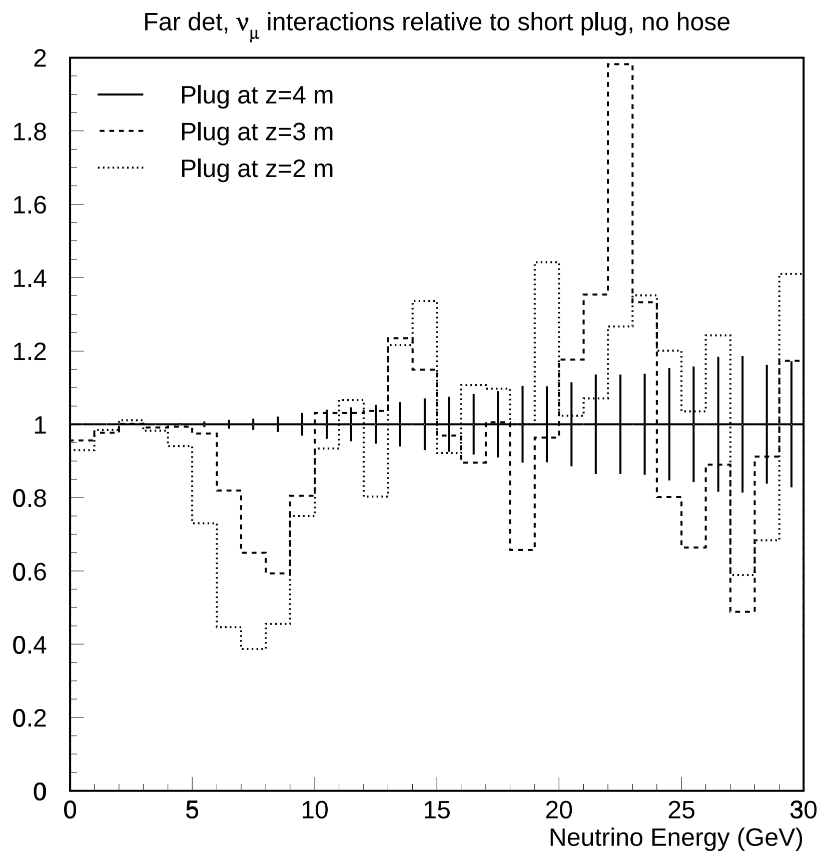

Figure 6: Far detector ν_μ interaction spectra relative to the short graphite beam plug at the nominal position of z = 4 m for the case of (dashed line) the short plug moved to z = 3 m (just past end of horn 1) and the case of (dotted line) the short plug moved to z = 2 m (inside the end of horn 1). The error bars show the statistical uncertainty of the spectrum with the plug at the nominal position normilized to the strength of this spectrum bin-by-bin. The statistics of the two cases with relocated plugs are half that of the nominal case. Note, the hadron hose is not used in this plot.

3.1 Alignment

To check the effects of misalignment of the plug on the far to near ratio, a Monte Carlo run with the plug rotated by 1.3 mrad (corresponding to a 1mm displacement in the positive X direction of the front face of the plug and a 1 mm displacement in the negative X direction of the back face) was done. Figure 7 shows the double ratio of the far to near ratio in the rotated case relative to that of the nominal case. The statistics get rather small starting in the shoulder and the tail of the energy spectrum, but through most of the peak there is less than 1% effects.

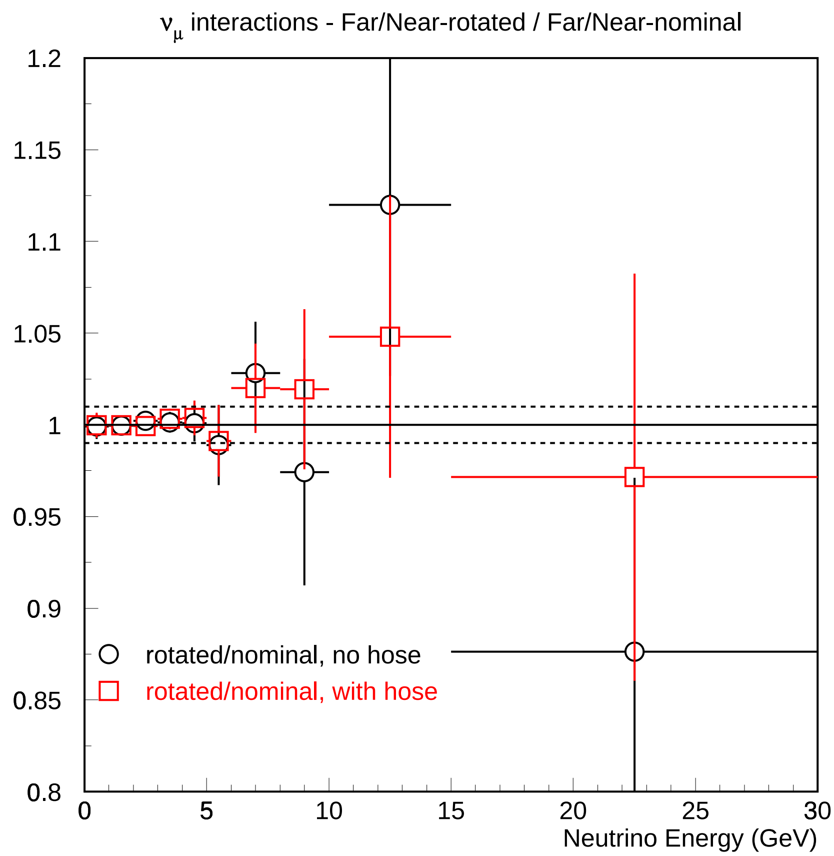

Figure 7: Double ratio of far over near for rotated case relative to nominal case for ν_μ interactions. Dashed lines show $\pm 1\%$. The plug is rotated 1.3 mrad (upstream face is 1mm in +x direction, downstream 1mm in -x direction).

3.2 The Bump in the Far/Near Ratio

The Far/Near ratio as calculated by Monte Carlo simulations is one way to extrapolate the near detector rates to give an expectation of what will be seen at the far detector. Obviously, understanding this ratio is crucial and the systematic uncertainty in this ratio must be minimized.

Figure 8 shows this ratio for ν_μ interactions in the case of no plug and in the case of the short graphite plug being used. For both, the hose is not included.

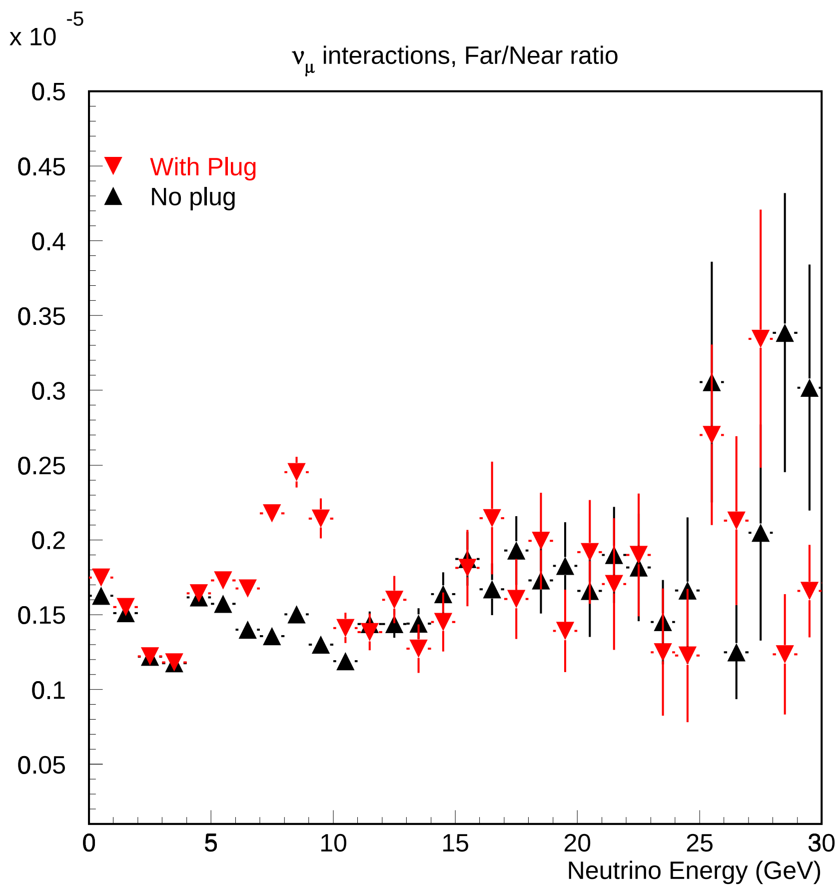

Figure 8: Far/Near ratio for ν_μ interactions with and without a plug (and no hose).

It is clear that the plug affects the Far/Near ratio quite strongly. There is a "bump" at about 8 GeV. To find the origin of this bump one must take a closer look at the components of the neutrino beam. To do this the neutrino parents are split into various sets depending on their trajectories through the target area.

3.2.1 Classes of Parent Tracks

The neutrinos come from an extended and not a point source. Furthermore, the source is very “nonlinear” due to the length of the target, the two focusing horns and, if used, the hadron hose. Additionally, the plug itself will add to this nonlinearity.

All in all, the final neutrino beam can be thought of as an admixture of several different “sub beams”. Each sub beam consists of all the neutrinos which, more or less, experience the same major perturbing elements. By studying these sub beams one can better understand how the different elements affect the aggregate beam, and how new elements will disturb this understanding.

To that end and to understand the 8 GeV bump in the Far/Near ratio, the beam was broken up into five different sub beams based on how the parent hadron was focused by the two horns [8]. To determine which horns focused which neutrino parent an approximation was used. Using the position and direction of the parent hadron as it left the target and ignoring any magnetic fields, the parent is tracked forward to see if it hits the first horn. Similarly, kinematic information at the parent's decay point is used to back track to the second horn. This approximation completely fails in the presence of the hose and thus is not considered here. Figure 9 shows a cartoon of the five possible tracks.

From the cartoon, the parent track type most expected to be affected by a plug is obviously the neck-neck (type 1) track. These parents are higher energy, and thus very forward going. Since higher energy parents will tend to produce higher energy neutrinos, it is no surprise why the plug works as it does. The second type, the neck-focused, as well as the fifth type, the over-focused parents will also have a chance to be absorbed by any beam plug. On the other hand, the third and forth types, the focus-neck and under-focused parents are expected to be least affected by any plug.

3.2.2 Spectra by Parent Track Type

Before tracking down the source of the 8 GeV bump, it is instructive to see the effect of the plug on the neutrino interaction spectra associated with each parent type. Figure 10 shows the contribution to the total ν_μ interaction spectrum from each parent in the case of near and far detectors both with and without a beam plug.

The lowest energy neutrinos come from the over-focus and the focus-neck parents. The bulk of the peak is filled by the under-focus parents, the rest of the peak, the shoulder and some of the tail is due to the neck-focus parents. The bulk of the tail (when no plug is in place) is due to the neck-neck parents.

The effect of the plug is obvious. As expected, the neck-neck parents are largely removed with little effect on the other parent types. The small reduction in the peak is mostly attributed to the over-focus parents.

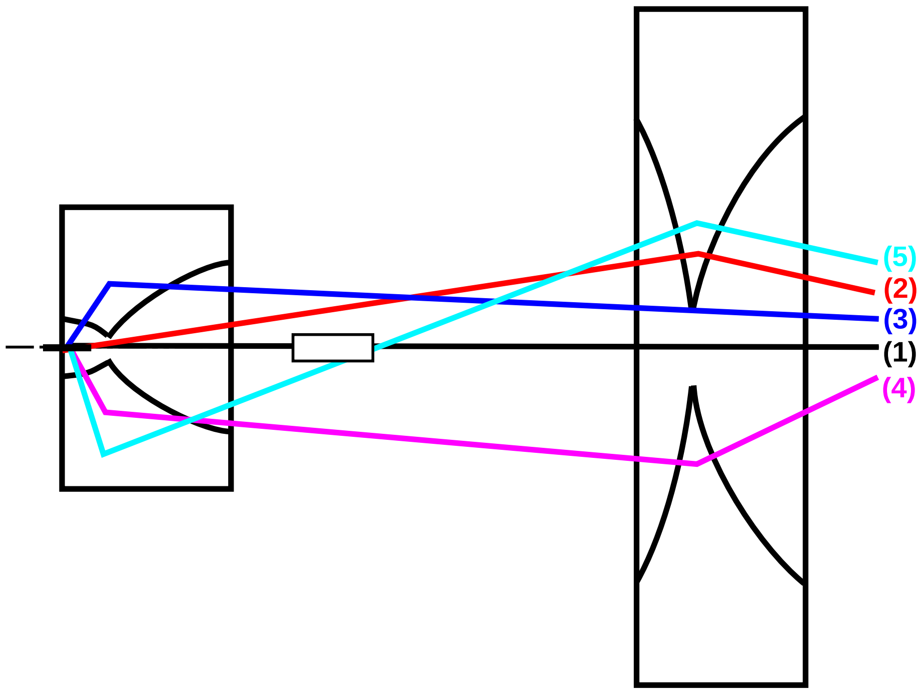

Figure 9: Five possible parent tracks differentiated by which horns, if any, provide the the focusing. The tracks are named (1) neck-neck, (2) neck-focus, (3) focus-neck, (4) under-focused, (5) over-focused.

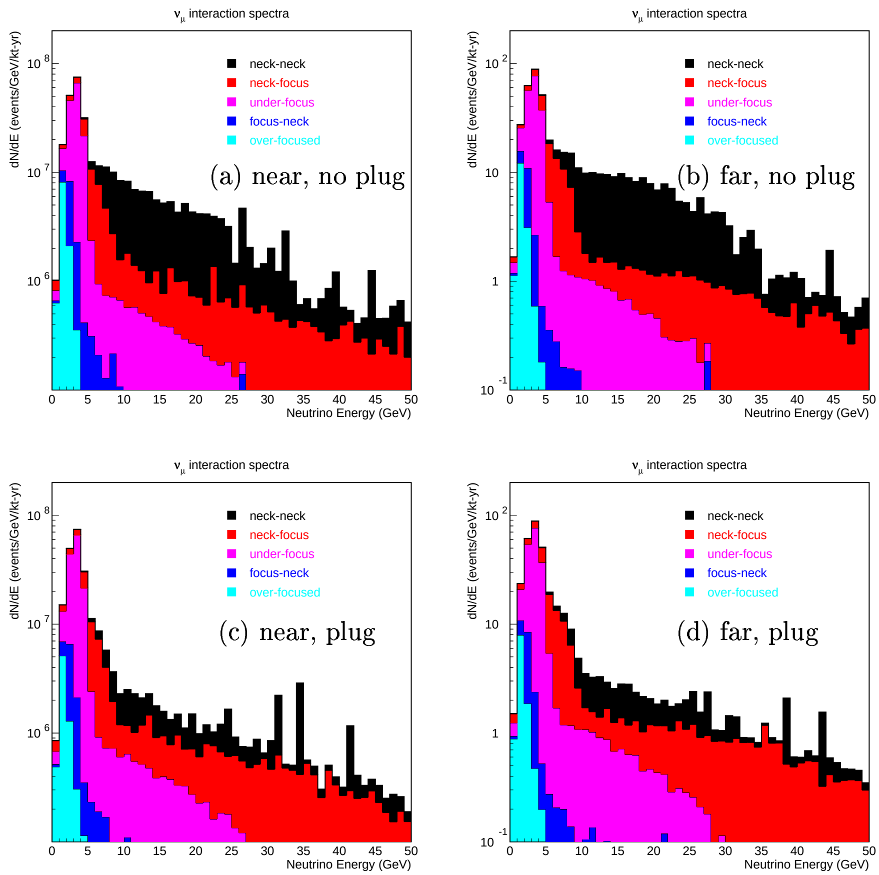

Figure 10: Fraction of ν_μ interaction spectra associated with each parent type in the case of (a) near and (b) far detector with out a plug and (c) near and (d) far detector with a plug. No hose is used here.

3.2.3 The Bump Revealed

Plotting the Far/Near ratio for ν_μ interactions as in Fig. 11 shows an interesting result. The bump exists even with out the plug, but only significantly in the the neck-focus spectrum. With the plug in place the bump is further enhanced.

The reason why the bumps exists in the case of no plug is due to the interaction spectrum in the far detector being slightly ($\sim$ 500 MeV) harder which in turn is due to the different kinematics needed to hit the near and far detectors. How this works is explained: The mean direction at time of decay of "useful" hadrons is about 4 mrad, while the near detector presents about 5 mrad cross section (at the mean decay point) and the far presents about 10 μrad. This means the angular phase space for a neutrino to hit the near detector is larger and has a higher average angle and thus a lower average energy. The energy of the parent hadrons responsible for those events which cause the 8 GeV bump are around 20 to 40 GeV. As an example, at the mean energy of 30 GeV a pion will produce an 8 GeV neutrino at 4.9 mrad, and higher energy neutrinos at lower angles. At any higher angle (lower energy) the neutrino would miss the far detector but still have a chance at hitting the near.

A second effect is seen when the beam plug is put in the beam. The plug causes the bump in the neck-focus spectrum to be increased (again, see Fig. 11). This is due to parents which tend to produce about 8 GeV neutrinos in the near detector getting absorbed by the beam plug. Lower energy parents (producing lower energy neutrinos) exit the target at a high enough angle to miss the beam plug, while higher energy parents tend to be too forward going to be classified as neck-focus. The reason this is not reflected in the far spectrum is that, due to details of the focusing, the coresponding neutrinos in the far detector tend to come from parents with slightly higher angles, and thus tend to miss the plug.

3.3 Dependence on the Hadron Production Model

We must rely to a large extent on Monte Carlo simulations to predict the flux at the far detector from that at the near detector. One source of systematic uncertainty in this prediction will be that associated with the neutrino parent hadron production model. This uncertanty can be guessed at by using various different hadron production models. Figure 12 shows the flux using GFLUKA and 3 other models: BMPT, MARS, Malensek (see [4] and refs therein). One can compare the non-plug plots with NuMI-B-700 [4] which were produced with an independent set of MC data. The fluxes are presented as the relative difference of each flux from the mean of the four. The non-GFLUKA fluxes are produced by reweighting the GFLUKA flux on a parent-by-parent case assuming the momentum of the incoming proton is that of the beam. Due to this assumption there will be some errors for the cases where the proton scatters before producing a parent hadron. The size of these error has not been estimated.

Since each of the non-GFLUKA fluxes are reweighted from the GFLUKA flux, they share the same statistics. The statistical uncertainties are shown for the GFLUKA case only and were calculated by simply normalizing the statistical

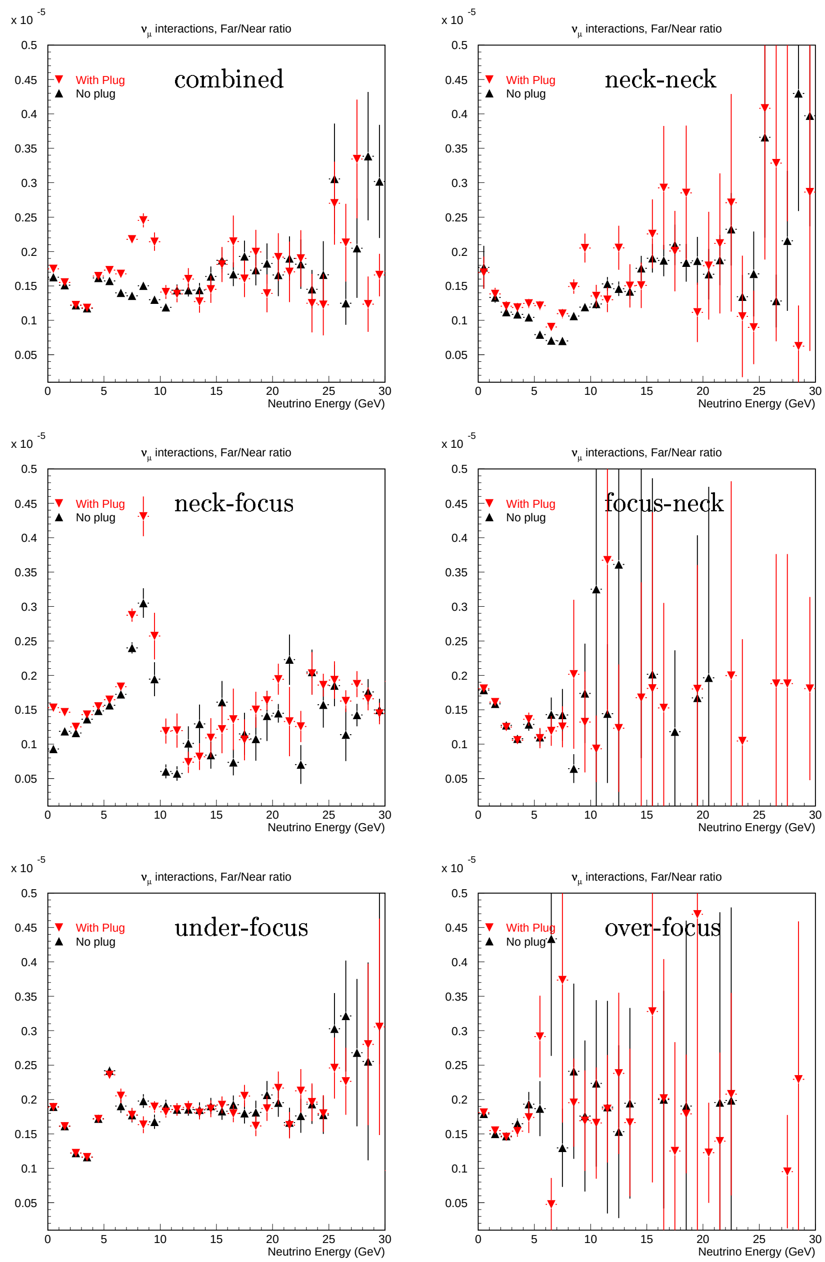

Figure 11: Far/Near ν_μ interaction spectra for all parent track types combined as well as for each individual parent track type in the case of both with and with out the short graphite plug.

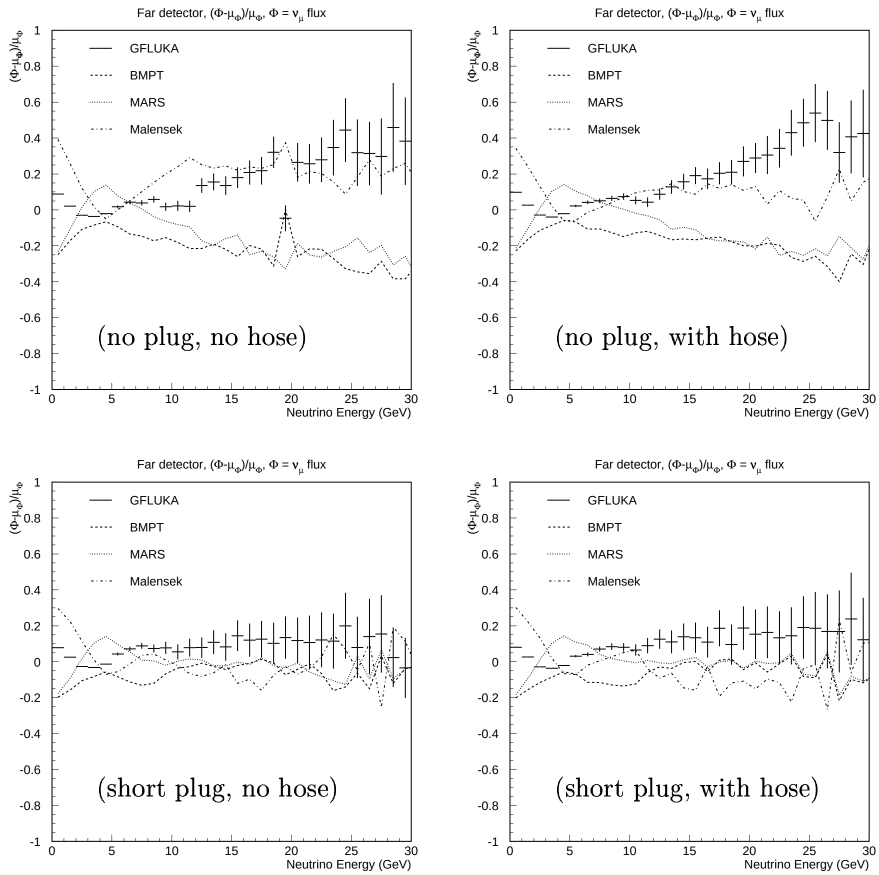

Figure 12: The difference of BMPT, MARS, Malensek and GFLUKA models from their means relative to their mean.

uncertainty in the raw flux by the average of the four fluxes, bin-by-bin.

With no plug there is some -20% to +40% spread in the deviation from average for these four fluxes. Adding the short graphite plug and irrespective of the hose, brings this upper limit down to about +20% in all but the first two GeV bins.

Since the above plots are relative to the average, they tend to be not as sensitive nor as transparent. So to present the same data in a different way, Fig. 13 shows the relationships more explicitly by plotting the expected far detector ν_μ flux from each reweighted model relative to the GFLUKA flux.

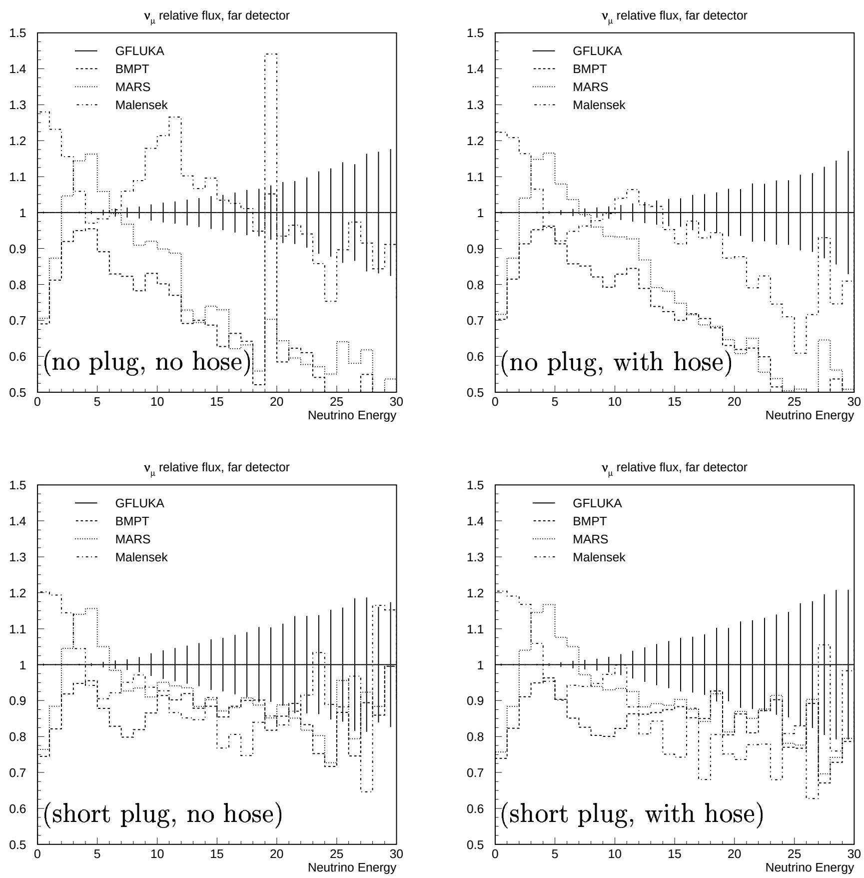

Figure 13: Flux spectra from BMPT, MARS and Malensek models relative to GFLUKA.

As before, the only statistical uncertainties are shown for the GFLUKA case (the line at $y = 1$) and are calculated by simply normalizing the raw uncertainties to the value of the GFLUKA flux, bin-by-bin. These plots show that the plug does a better job than the hose at reducing the dependence on the production model, particularly for the higher energy neutrinos.

Figure 14 shows the far/near ratio of the flux spectra for each of the three non-GFLUKA production models relative to that of the GFLUKA model for the various combinations of plug and hose. There is no strongly significant deviations in the tails of the spectra and so only the region less than 15 GeV is shown.

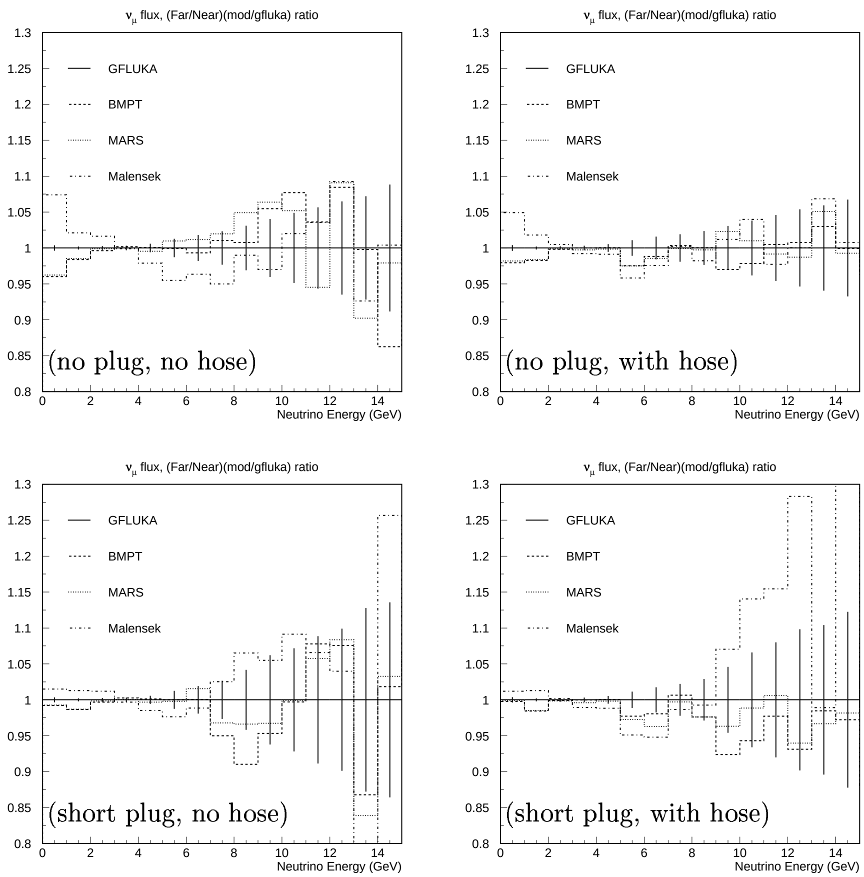

Figure 14: Far/Near ratio of flux spectra from BMPT, MARS and Malensek models relative to ratio for the GFLUKA model.

The plug alone does a slightly better job of collapsing the different models in the region of the low energy peak of the spectrum than does the hose. However, the magnitude of the the "8 GeV bump" (see section 3.2.3) can be seen to be slightly dependent on the details of the hadron production model. This dependence moves to around 11 GeV when the hose is turned on. (It is not discussed in this note, but the "8 GeV bump" in the GFLUKA produced far/near ratio becomes a bump an "11 GeV bump" when the hose is turned on).

4 Conclusions

Inserting a beam plug reduces the high energy tail of the muon neutrino interaction spectrum in the far detector by about 70% over what the base line plus hadron hose case gives. This also reduces the low energy peak by about 5%. Cutting back the high energy tail is important in reducing the NC contamination in $\nu_\mu \to \nu_e$ searches. There is room to improve these values by optimizing beam plug design and placement. In particular, capping the graphite beam plug with copper will further reduce the tail and moving the beam plug closer to the first horn will reduce the shoulder of the spectrum.

The systematics associated with the plug were studied. The spectrum is not strongly sensitive to alignment of the plug, but the plug uncovers and enhances a bump at 8 GeV in the ratio of interaction spectra in the far detector relative to that in the near. This bump is primarily independent from the plug. It is uncovered because the plug removes most of the neutrinos from parents which pass through the neck of each horn (neck-neck parents). This allows neutrinos from neck-focus parents to dominate the spectrum around 8 GeV. It is these parents which produce the bump because of geometrical considerations and decay angle phase space. Additionally, the plug enhances this bump as it preferentially removes parents produced at small angles and the near detector is slightly more sensitive to the higher energy neutrinos which would come from these parents. This results in an additional hardening of the far detector spectrum relative to that of the near detector and thus an increase in the magnitude of the bump.

The dependence of the spectra on the hadron production model was also studied. The plug appears to minimize the difference between the models as well as or better than the hose, particularly at higher energies. However the sensitivity to parents producing 8 GeV neutrinos, which the plug uncovers and enhances, causes a significant splitting between the spectra from the different models in this energy region.

What was not studied is any detailed optimization, environmental effects (beam heating, radiation limits) or costs. This and other work must be done in order to consider the feasibility and ultimate desirability of implementing a beam plug.

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[9] See http://minos.phy.bnl.gov/~bviren/minos/beamplug/ for source code and data files used in this note.

List of Figures

List of Tables